APPENDIX C

Air Velocity Measurement and Flow Rate Calculation

C-1. Airflow rate measurements can be made using a variety of flowmeters, including rotameters, hot-wire anemometers, and flowmeters based on a differential pressure reading inside the pipe. Differential pressure related flowmeters include venturi meters, orifice plates, averaging pitot, and pitot tubes. Pitot tubes, rotameters, and hot-wire anemometers are typically the most appropriate and most commonly used measuring devices for IAS applications. Accurate measurements of airflow rates in IAS piping requires understanding the principles of operation of the flowmeter used. A reading of a velocity or flow rate on a flowmeter can represent different real volumetric flow rates, depending on parameters such as air temperature and pressure. A discussion of how to calculate the real volumetric flow rate in an IAS pipe follows.

C-2. Figure C-1 shows a pitot tube installed in a small diameter pipe. To accurately measure the flow rate of air in this pipe, it is important to consider the physics of airflow in the pipe and the operation of the pitot tube. These considerations for the pitot tube can also be applied to the other flowmeters mentioned above.

a. The pitot tube consists of two pressure ports, one perpendicular to flow (static pressure port) and one pointed directly into the flow (stagnation or total pressure port). The differential pressure between these two ports is referred to as the velocity pressure and is a function of velocity.

b. Bernoulli's equation can be used to derive the relationship between velocity and velocity pressure:

$$p_t + h_t + v_t^2/(2g) = p_s + h_s + v_s/(2g) \quad \text{[Bernoulli's equation.]} \tag{C-1}$$

where the subscript *t* represents the property at the total pressure port and the subscript *s* represents the static pressure port. For IAS systems, $h_t = h_s$ and $v_s = 0$. Therefore:

$$\Delta p = p_s - p_t = v_t^2/(2g) \tag{C-2}$$

and

$$v = v_t = \sqrt{2g\Delta p} \tag{C-3}$$

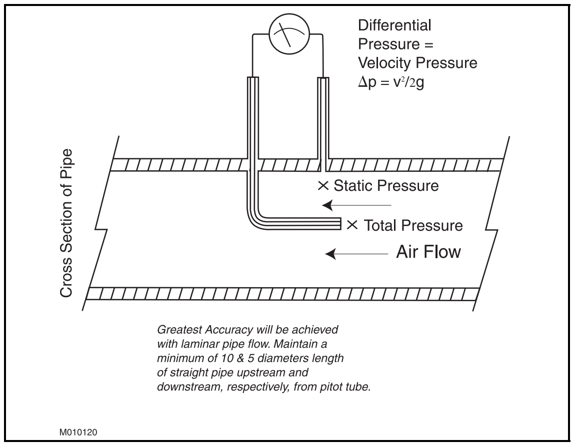

Figure C-1. Pitot tube flow measurement schematic.

In equation C-3, the differential pressure (or velocity pressure) is the height of fluid (air) and velocity is in length per unit time. However, differential pressure gauges do not have "height of air" scales, but usually have scales in units of mm water, cm water, or mm mercury (Hg) (or inches of water). Differential pressure may also be reported as pascals (ΔP; force per unit area), which can be related to height of fluid: $\Delta P = \rho_{\text{air}} \times g \times \Delta p$. Rearranging and substituting into equation C-3 gives:

$$v_t = \sqrt{2\Delta P / \rho_{\text{air}}} \tag{C-4}$$

Height of fluid is related to units for the measuring device (i.e., height of water or height of mercury) by: $\Delta p_{\text{air}} = \Delta p_{\text{md}} \times \rho_{\text{md}} / \rho_{\text{air}}$, where *md* refers to the units for the measuring device (e.g., mm of water). Therefore:

$$v_t = \sqrt{2g\Delta p_{\text{md}} \frac{\rho_{\text{md}}}{\rho_{\text{air}}}} \tag{C-5}$$

Note again that velocity for the pitot tube is a function of the density of air. Only when $\rho_{\text{air}} = \rho_s = \rho_{\text{standard}}$, where the pressure and temperature at the static pressure port is at standard conditions (i.e., 20°C and 1 atm), can standardized charts be used without a correction for temperature and pressure.

c. Pitot tubes relate velocity to pressure at the point of the stagnation port, generally placed in the center of the pipe. IAS systems typically use pipe smaller than 150 mm, and measuring the velocity in the pipe at any point other than the center of the pipe is not practical. The velocity at the center of the pipe is the maximum velocity within the pipe and the velocity near the wall of the pipe approaches zero. Best engineering practice for compensating for the non-uniform velocity profile across the cross section of the pipe is to use an integrated average velocity, often assumed to be 0.9 times the velocity in the center of the pipe. The velocity is used to calculate the volumetric flow rate, Q. Typically the measured flowrate, Q_{measured}, is obtained by assuming that the measurement point is at standard temperature and pressure conditions, i.e., $\rho_{\text{air}} = \rho_{\text{standard}} = 1.2$ kg/m^3. For differential pressure expressed as force per area (e.g., pressure in Pascals or psi):

$$Q_{\text{measured}} = 0.9 \frac{\pi\, d^2}{4} \sqrt{2\Delta P / \rho_{\text{standard}}} \tag{C-6}$$

or

$$Q_{measured} = 1.0\, d^2 \sqrt{\Delta P / \rho_{\text{standard}}} \tag{C-7}$$

For differential pressure expressed as height of water or height of mercury:

$$Q_{\text{measured}} = 0.9 \frac{\pi\, d^2}{4} \sqrt{2 g \Delta p_{\text{md}} \frac{\rho_{\text{md}}}{\rho_{\text{standard}}}} \tag{C-8}$$

or

$$Q_{\text{measured}} = 1.0\, d^2 \sqrt{g \Delta p_{\text{md}} \frac{\rho_{\text{md}}}{\rho_{\text{standard}}}} \tag{C-9}$$

d. Larger pipe can be fitted with a pitot tube that is constructed of concentric tubes that has the static pressure port located in the outer tube, while the stagnation pressure port is the tip of the inner tube.

e. Averaging pitot tubes work on the same principle of relating differential pressure within the pipe to airflow rate. Differential pressure is obtained with an averaging pitot tube by measuring pressure at ports in the upstream and downstream sides of a tube (typically 8 to 16 mm diameter) inserted into the pipe perpendicular to flow. There are a series of pressure ports along the tube that pneumatically “average” the differential pressure profile of the cross section of the pipe. The equations relating this average differential pressure to flow rate are specific to each averaging pitot tube manufacturer. Averaging pitot tubes are more accurate than conventional pitot tubes and can easily be moved from one measurement location to another. Thus, by simply installing measurement ports with compression seals at various locations in an SVE/BV system, flow measurements can be made for the system using a single averaging pitot tube and differential pressure gauge.

f. It is desirable to report flow rates normalized to a standard temperature and pressure so that flows can be readily compared. Airflow measuring equipment may be calibrated to air at different temperature and pressure than the air flowing through the IAS system. (If airflow measuring equipment is calibrated, it is typically calibrated at standard conditions.) Calibrated gauges must be matched to the correct measuring devices and inside pipe diameter. In some instances, the gauges will have dual scales, with one scale indicating the velocity pressure, and the other indicating the air velocity or flow rate. Direct velocity or flow readings must be corrected to account for the differences between the temperature and pressure of the air being measured, and the temperature and air when the instrument was calibrated. The temperature and pressure (and therefore density) of air from an IAS compressor will be a large deviation from standard conditions. *Only at the calibrated density would a flowmeter not require correction to obtain a standardized flow rate or velocity.* With the exception of high-end electronic flow meters that can compute an internal correction for air at the measured temperature and pressure (i.e., density), air flowmeters do not provide a direct reading (i.e., without needing correction for air density) of standard flow or actual flow. (Standard flow refers to the equivalent flow rate if the air was flowing at standard conditions. Actual flow refers to the flow rate at the temperature and pressure that exists at the point of measurement.)

g. "Measured" flow rate may be directly read from a gauge that has a scale for direct reading of airflow rates, or may be stored electronically by a datalogger in a system with automated data acquisition. The corrected standardized flow rate (Q_{standard}) is equal to the product of the measured flow rate (Q_{measured}) and the square root of the ratio of the density at the calibrated (standard) conditions and the density of the air being measured.

$$Q_{\text{standard}} = Q_{\text{measured}} \sqrt{\frac{\rho_{\text{actual}}}{\rho_{\text{calibrated}}}} \tag{C-10}$$

Applying the ideal gas law to the density ratio provides a more practical correction equation:

$$Q_{\text{standard}} = Q_{\text{measured}} \sqrt{\frac{273 + T_{\text{calibrated}}}{273 + T_{\text{actual}}} \cdot \frac{760 + P_g}{P_{\text{calibrated}}}} \tag{C-11}$$

where

P_g = gauge pressure in mm Hg
T = temperature in °C
$P_{\text{calibrated}}$ = absolute pressure in mm Hg at the calibrated conditions.

Applying the assumption of calibration at standard conditions:

$$Q_{\text{standard}} = Q_{\text{measured}} \sqrt{\frac{293}{273 + T_{\text{actual}}} \cdot \frac{760 + P_g}{760}} \tag{C-12}$$

or

$$Q_{\text{standard}} = K_{pt} Q_{\text{measured}} \tag{C-13}$$

where K_{pt} is the Correction Factor shown in equation C-12. For convenience, Figure C-2 presents a nomograph of K_{pt} that can be used to correct measured values to standard ones.

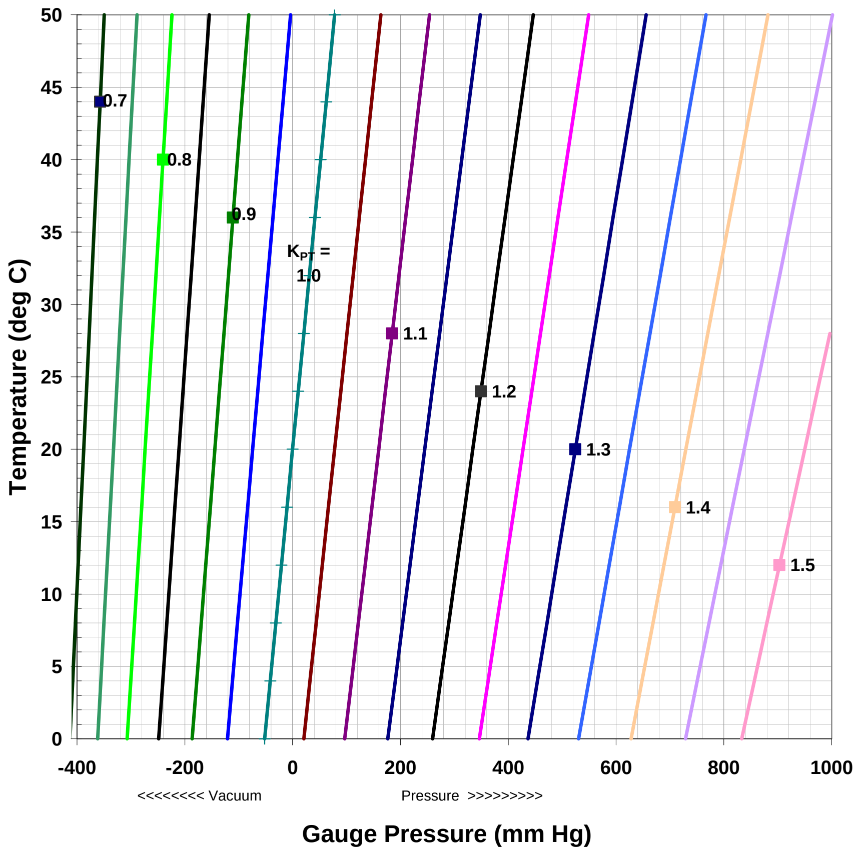

Figure C-2. Nomograph of flow correction factors (K_{PT}) for converting measured flow (at temperature and pressure different from STP) to standardized flow (i.e., flow rate at standard temperature and pressure).

h. The correction factor described by equations C-12 and C-13 is necessary for measurements made using rotameters and for volumetric airflow measurements based on a differential pressure measurement, such as pitot tubes, venturi meters, and orifice plates. In contrast, hot-wire anemometers measure the mass flux of air flowing past a hot wire and the anemometers' readouts typically yield velocities as if the flow was under standard temperature and pressure. (Note that if the actual temperature of the air being measured is close to the temperature of the hot wire, e.g., at the outlet of a thermal oxidizer, then this device may not provide an accurate flow measurement.)

i. An alternate method for calculating Q_{standard} is to calculate Q_{actual} (the actual air flow rate) using the actual temperature and pressure values at the measurement point, and then converting to a standard flow rate as shown below.

$$\rho_{\text{actual}} = \frac{(0.463\,P_a)}{(273 + T_{\text{actual}})} \qquad \text{(C-14)}$$

In the above equation, density units are kg/m^3, using units of degrees Celsius and mm Hg for temperature and absolute pressure (P_a), respectively. In the following equation, airflow rate is obtained in m^3/min., using units of meters for inside diameter (d), mm Hg for velocity pressure (Δp_{md}), and kg/m^3 for air density (ρ_{actual}).

$$Q_{\text{actual}} = 0.9\,\frac{\pi\, d^2}{4}\,978.1\sqrt{\Delta p_{\text{md}} / \rho_{\text{actual}}} \qquad \text{(C-15)}$$

Q_{actual} is then converted into a standard flow rate using the following equation. In the following equation, mm Hg and degrees C are used as units for gauge pressure (P_g) and temperature, respectively.

$$Q_{\text{standard}} = Q_{\text{actual}}\,\frac{293}{273 + T_{\text{actual}}} \cdot \frac{760 + P_g}{760} \qquad \text{(C-16)}$$